Cosmic Rays and our local environment :
A silicon based particle detector for space-borne experiments

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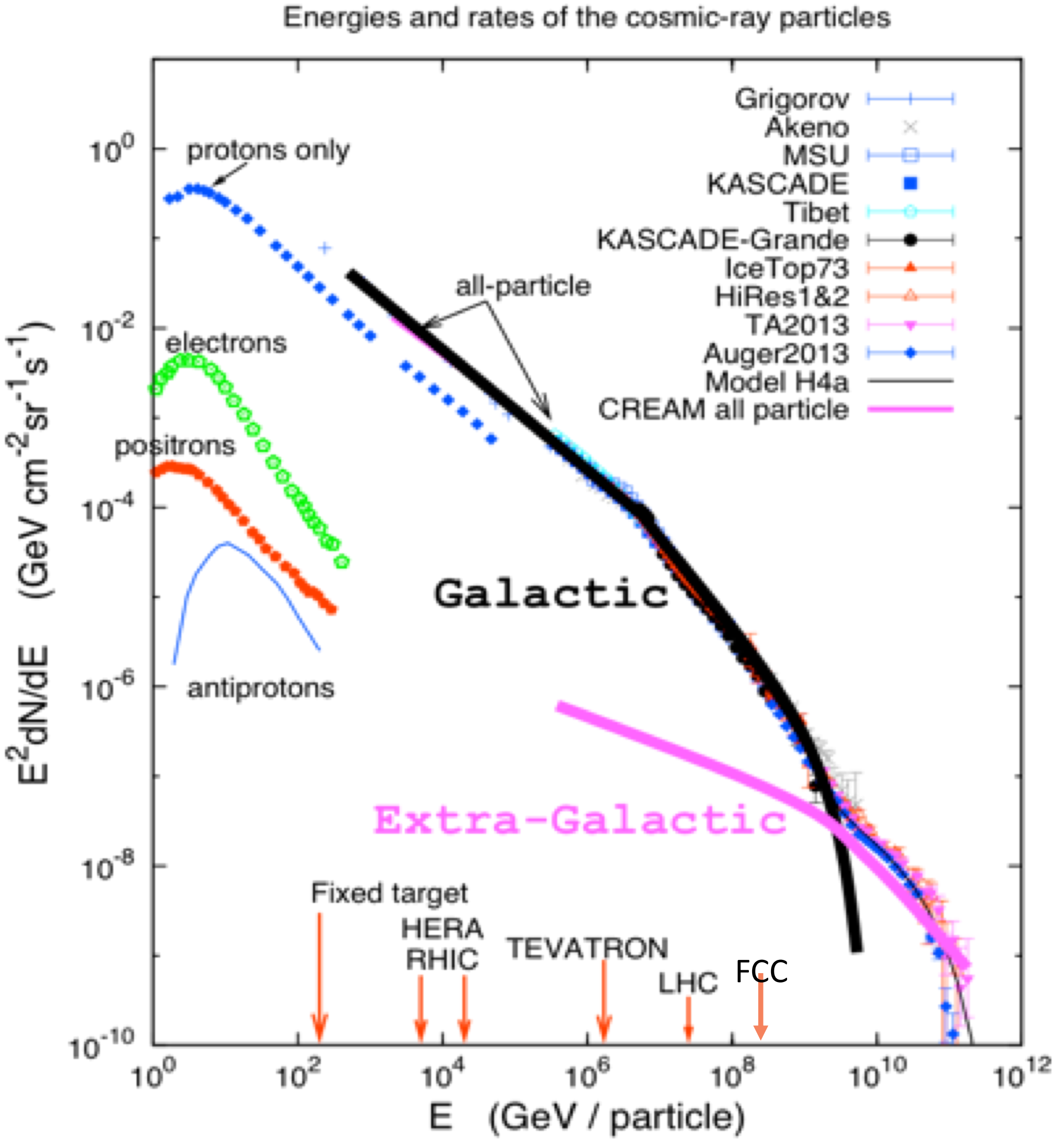
This talk

- Will briefly review the current status of CR transport modelling and the instruments which deliver data for it.

- Our capabilities to build a similar detector as well as ISRO launch capabilities.

- Make a case for an endurance frontier, multi decade long mission(s) to map out the heliosphere and beyond in space and time.

The ‘Standard Model’ of Cosmic Ray Physics



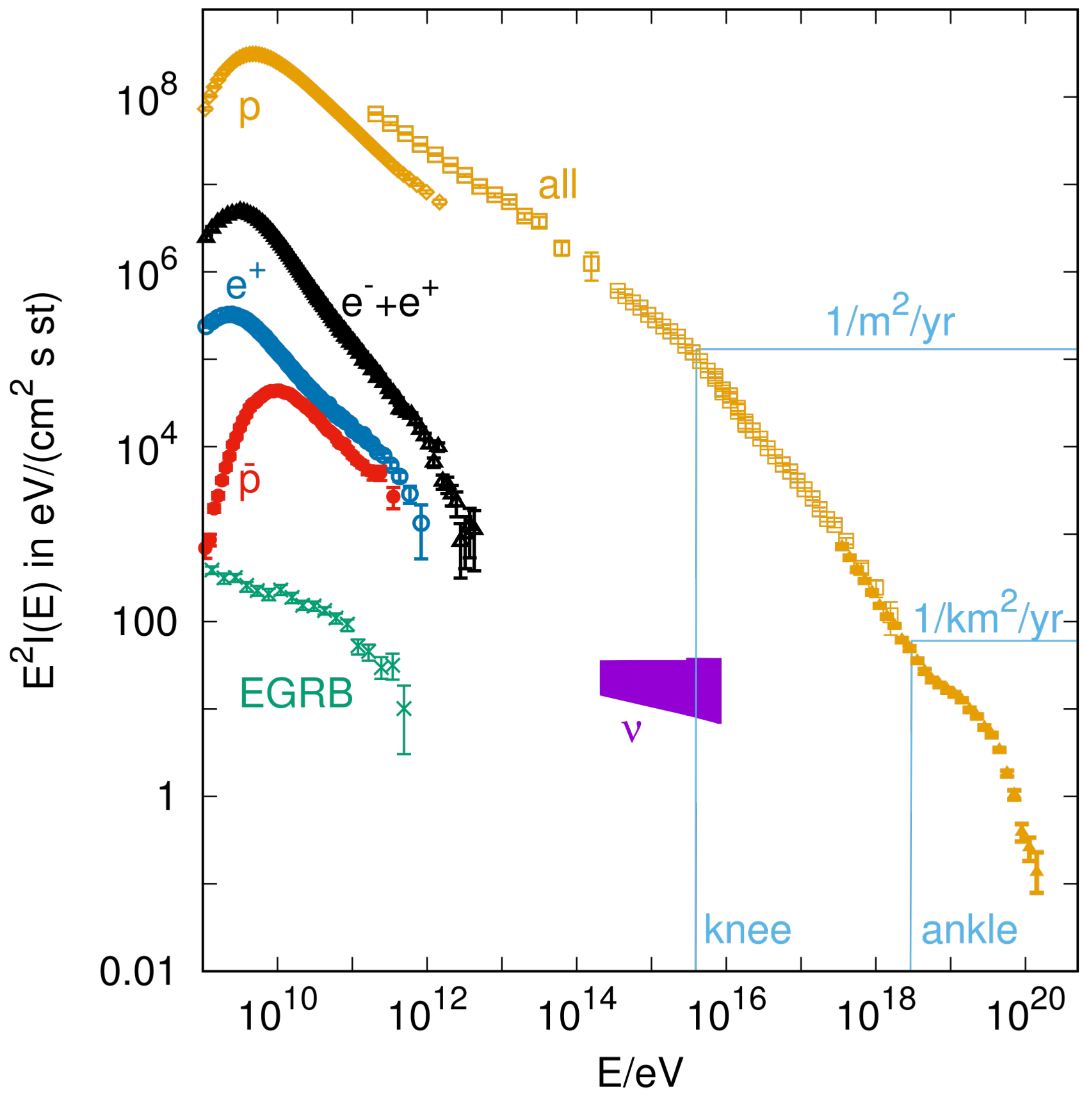
Magnetic Reconnection and Shock Acceleration at Solar CMEs, up to 10s of GeV

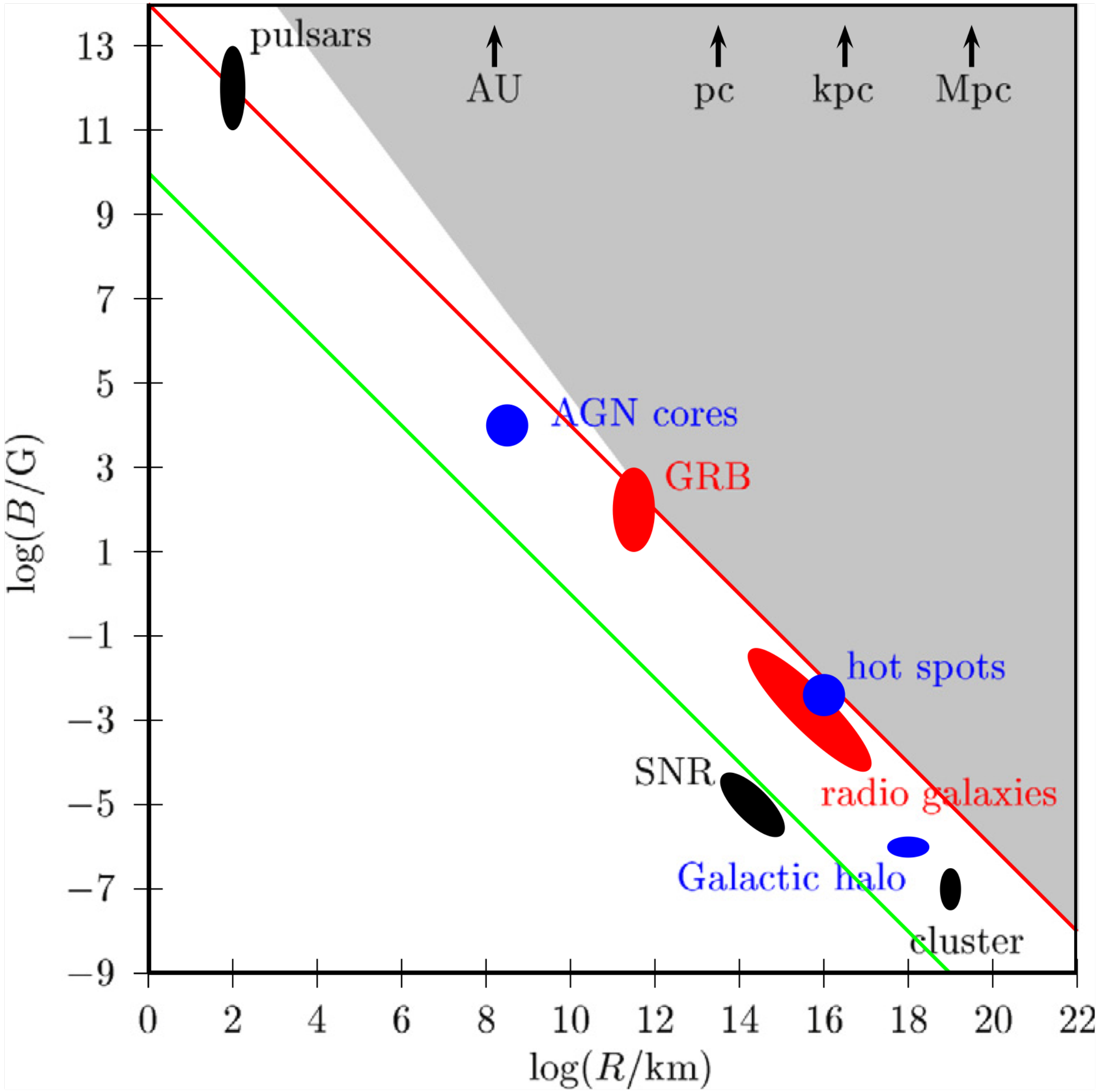
Diffusive Shock Acceleration at SuperNova Remnant Shocks (up to Knee) ~ 2 SNs/century/Galaxy – 10^{50} ergs/SN

γ-ray observations of SNRs support this picture (somewhat)

Knee to Ankle – Transition from Galactic to Extragalactic

Above Ankle - Extragalactic


p
all
e+
e-+e+
p̄
EGRB
ν
1/m2/yr
1/km2/yr
knee
ankle
E2I(E) in eV/(cm2 s st)
E/eV
0.01
1
100
10^4
10^6
10^8
10^10
10^12
10^14
10^16
10^18
10^20


pulsars
AU
pc
kpc
Mpc
AGN cores
GRB
hot spots
radio galaxies
SNR
Galactic halo
cluster
log(B/G)
log(R/km)
13
11
9
7
5
3
1
−1
−3
−5
−7
−9
0
2
4
6
8
10
12
14
16
18
20
22

Cosmic Ray transport in the 'Standard Model'

Real and momentum space diffusion, advection, continuous energy losses

$$\frac{\partial n^{(a)}}{\partial t} - \nabla_i \left[D_{ij}\nabla_j - u_i\right] n^{(a)} - \frac{\partial}{\partial p}\left[p^2 D^{(p)} \frac{\partial}{\partial p} p^{-2} n^{(a)}\right] = -\frac{\partial}{\partial p}\left(\beta^{(a)} n^{(a)}\right)$$

$$-\left(c n_{\rm gas} \sigma^{(a)}_{\rm inel} + \Gamma^{(a)}\right) n^{(a)} + Q^{(a)} + \sum_b \left[c n_{\rm gas} \int_E^\infty dE' \, \frac{{\rm d}\sigma^{ba}(E', E)}{{\rm d}E} + \Gamma^{ba}\right] n^{(b)} .$$

Gain and loss processes, injection, decay, spallation etc

Kacherleiss & Semikoz 2019

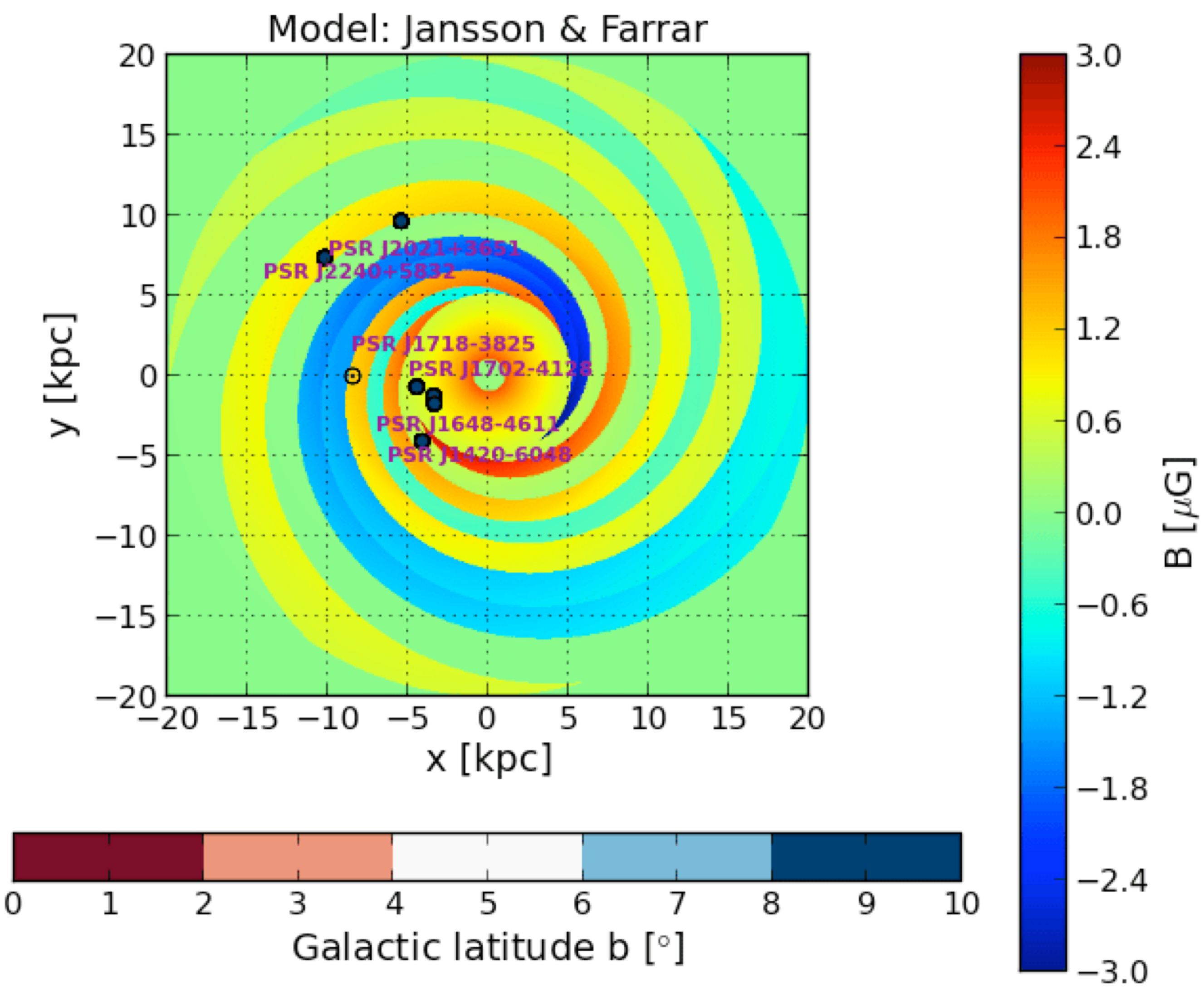
Not tractable so needs to be simplified :

$D_{ij}, \vec{u}, Q, \beta, \boldsymbol{n_{gas}}$ assumed to be isotropic and homogeneous (within a cylindrical model of Galaxy) for tractability
Injection specta of $E^{-\alpha}$ with rigidity dependent cutoff, $\alpha \sim 2.0 - 2.2$
Abundance of different species at injection $Q_0^{(a)}$ usually **fit to data or or chosen close to Solar ones**, its spatial dependence is modelled according to the observed distributions of SNe or Pulsars, with spiral structure of Galactic disc and also the Galactic bulge typically ignored

Momentum space diffusion due to electromagnetic fields lead to **reacceleration, poorly constrained** (Drury & Strong 2017)

Implemented in GALPROP, https://galprop.stanford.edu/

The Galactic Magnetic Field is not uniform according to our current knowledge

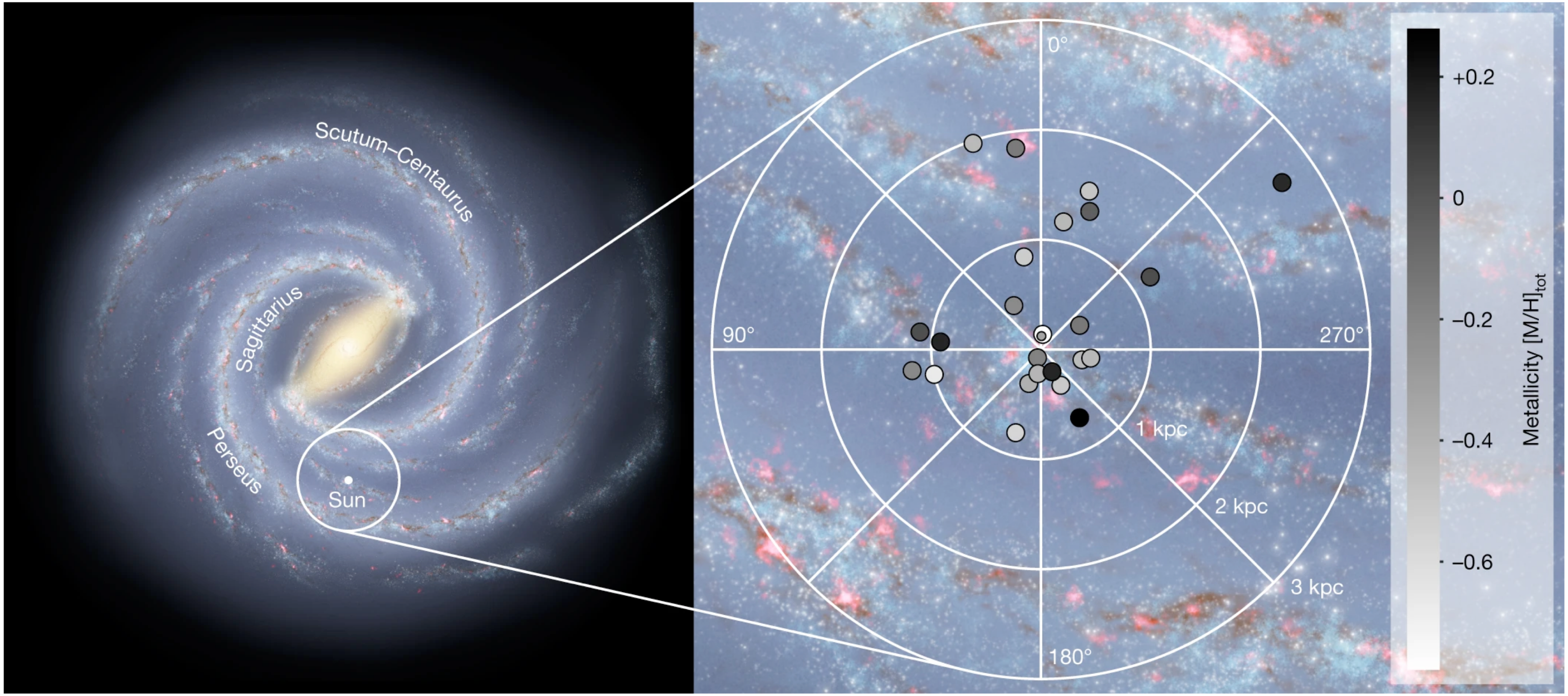


Model constructed using Faraday Rotation measurements in Radio

Since many sources contribute, the discrete nature of the CR sources can be neglected. This allows one to consider the stationary limit of Eq. (4) and to use a smooth, time-independent source distribution Q (x). As a second approximation, one also neglects the spatial dependence of the diffusion term, replacing the Galaxy by a cylinder with uniform propagation properties for CRs. Finally, one replaces often the tensor D_{ij} by a scalar diffusion coefficient D, assuming that the turbulent field dominates relative to the regular field. **Note that the last two approximations clearly contradict our knowledge of the GFM** which indicates a strong variation of the magnetic field strength, both as function of galactocentric radius and distance to the Galactic plane, as well as an anisotropic diffusion of CRs. **These approximations imply that the fit results derived in such diffusion models for, e.g. the normalisation D_0 of the diffusion coefficient, can be seen only as effective parameters.**

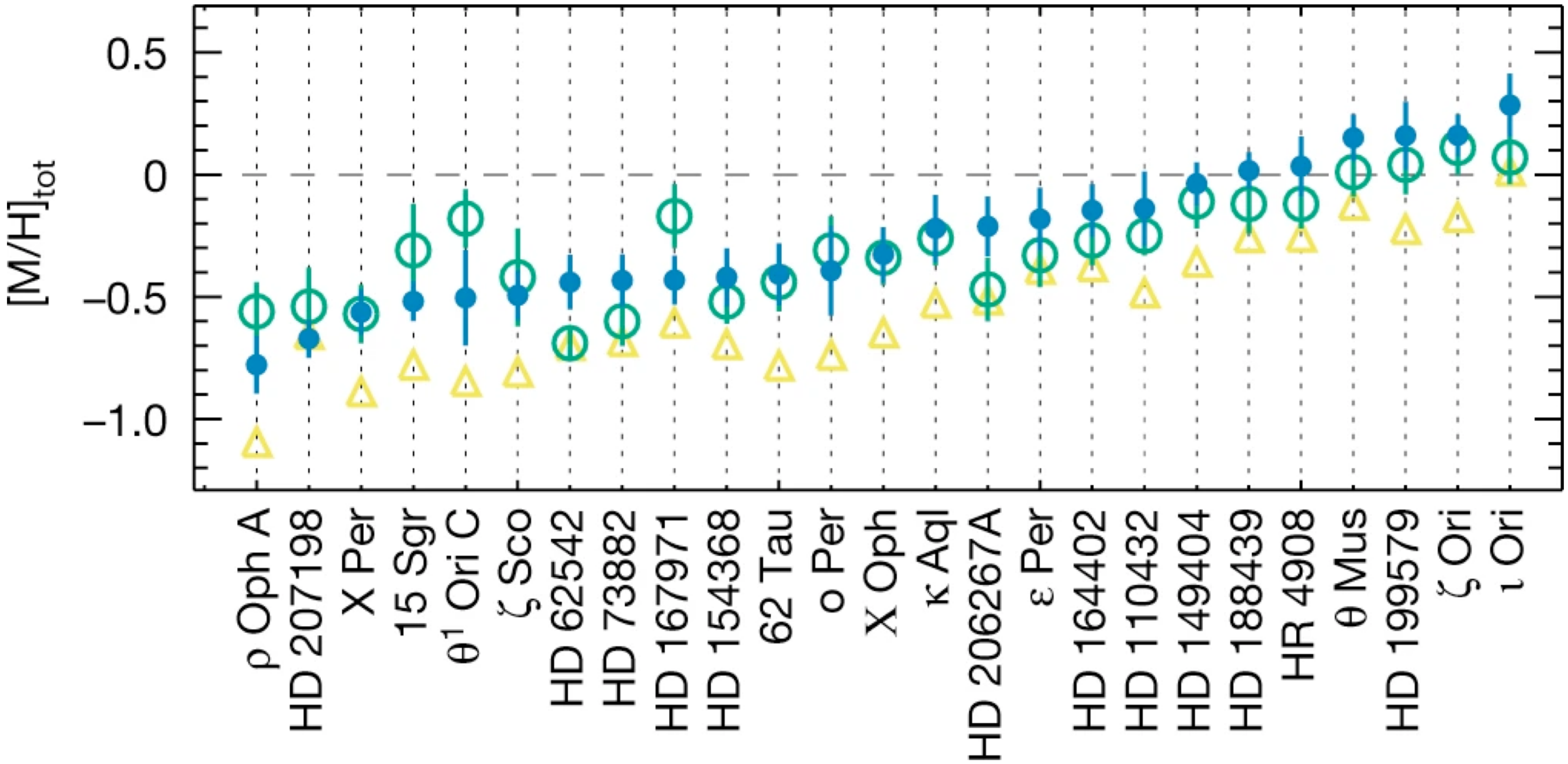
Kacherleiss & Semikoz 2019

Recently n_{gas} was found to be highly inhomogeneous



De Cia et al. *Nature* **597**, 206–208 (2021)

Gas along 15 out of 25 lines of sight had metallicity more than 3 sigma away from solar metallicity



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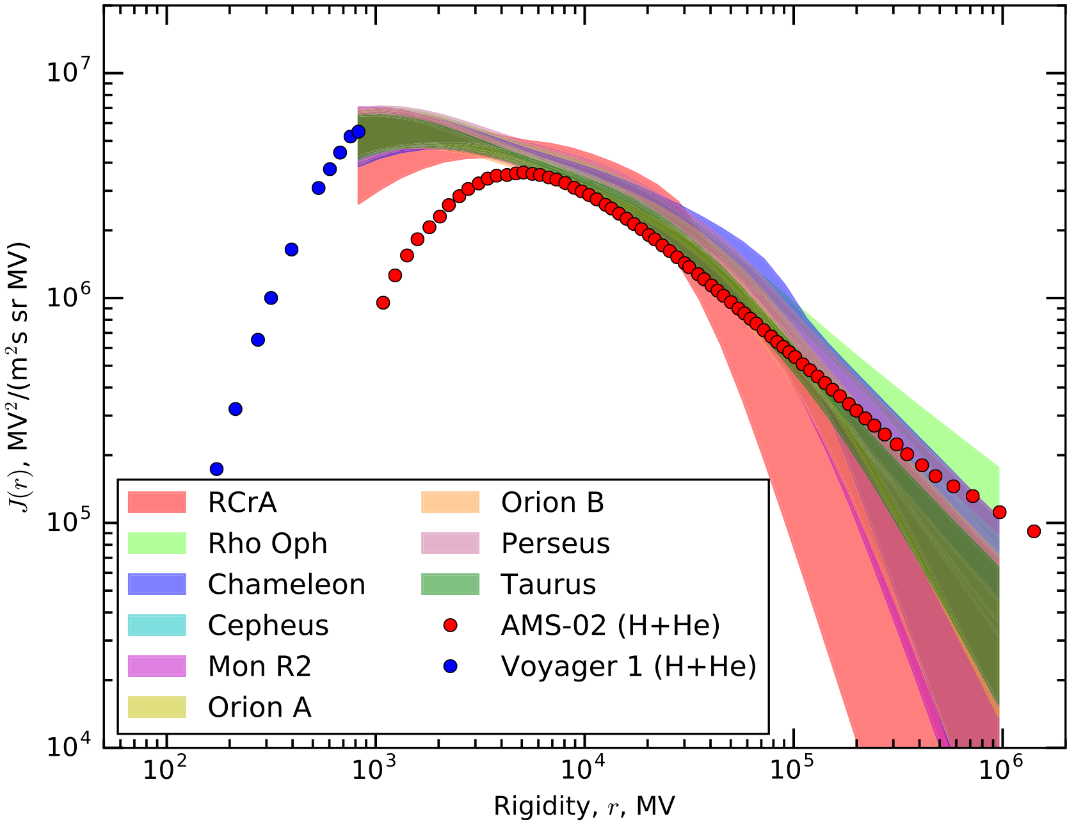
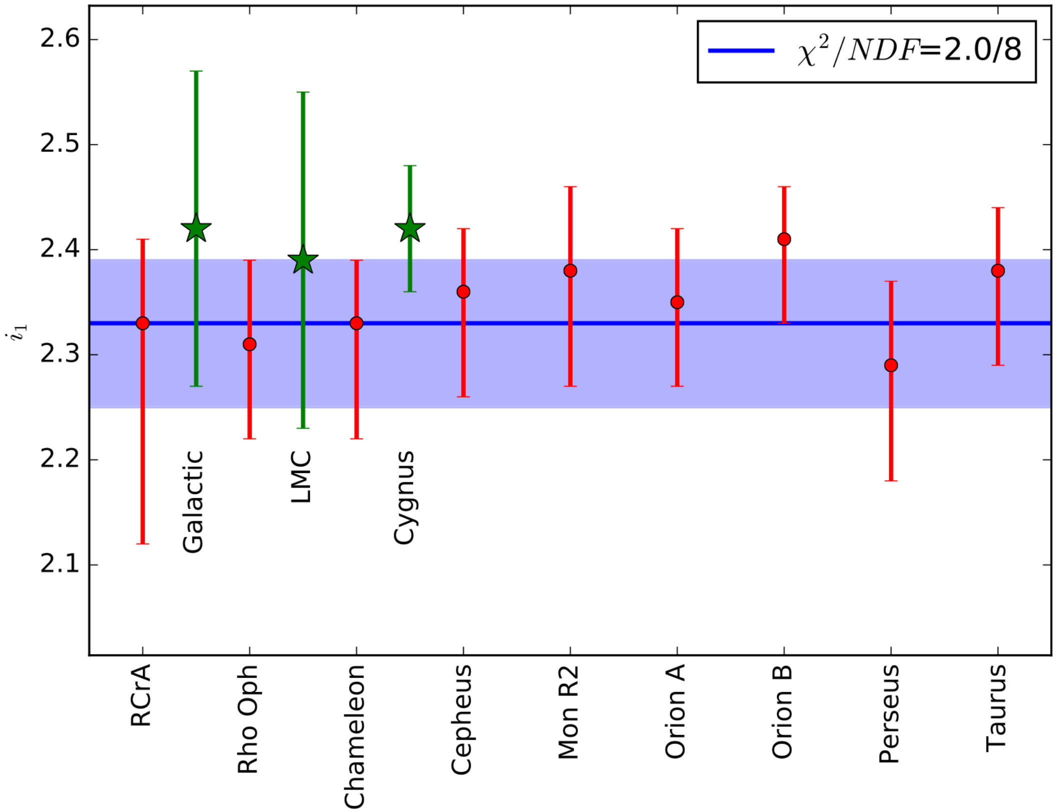
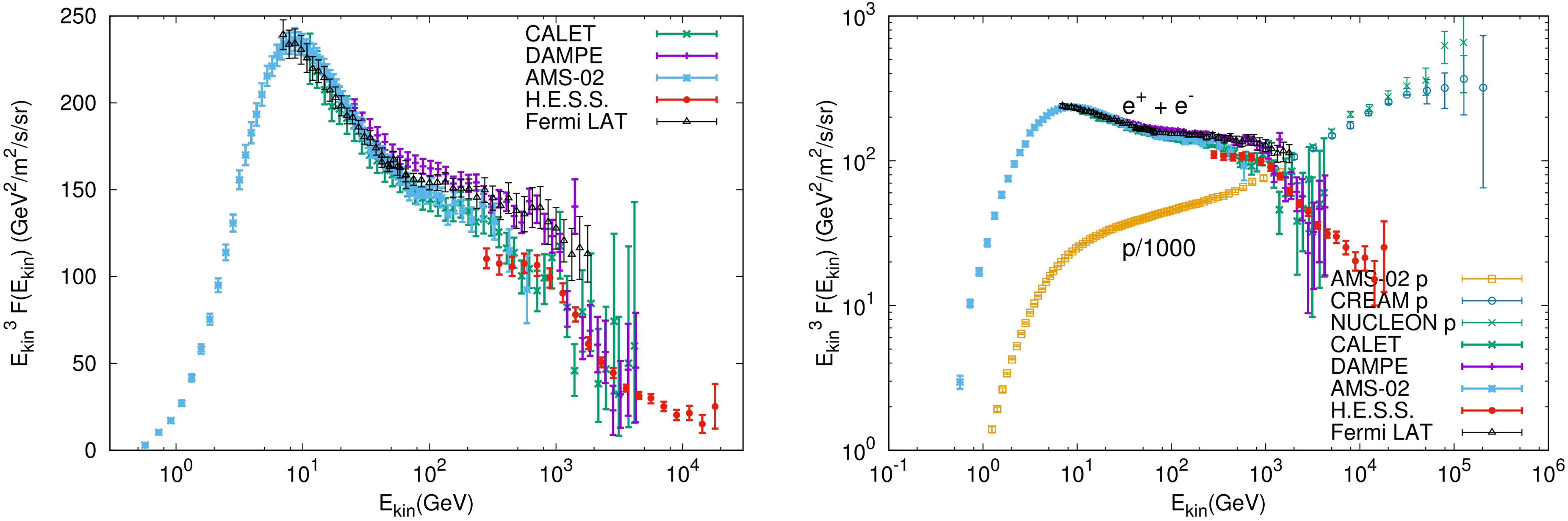
The models nevertheless can fit data

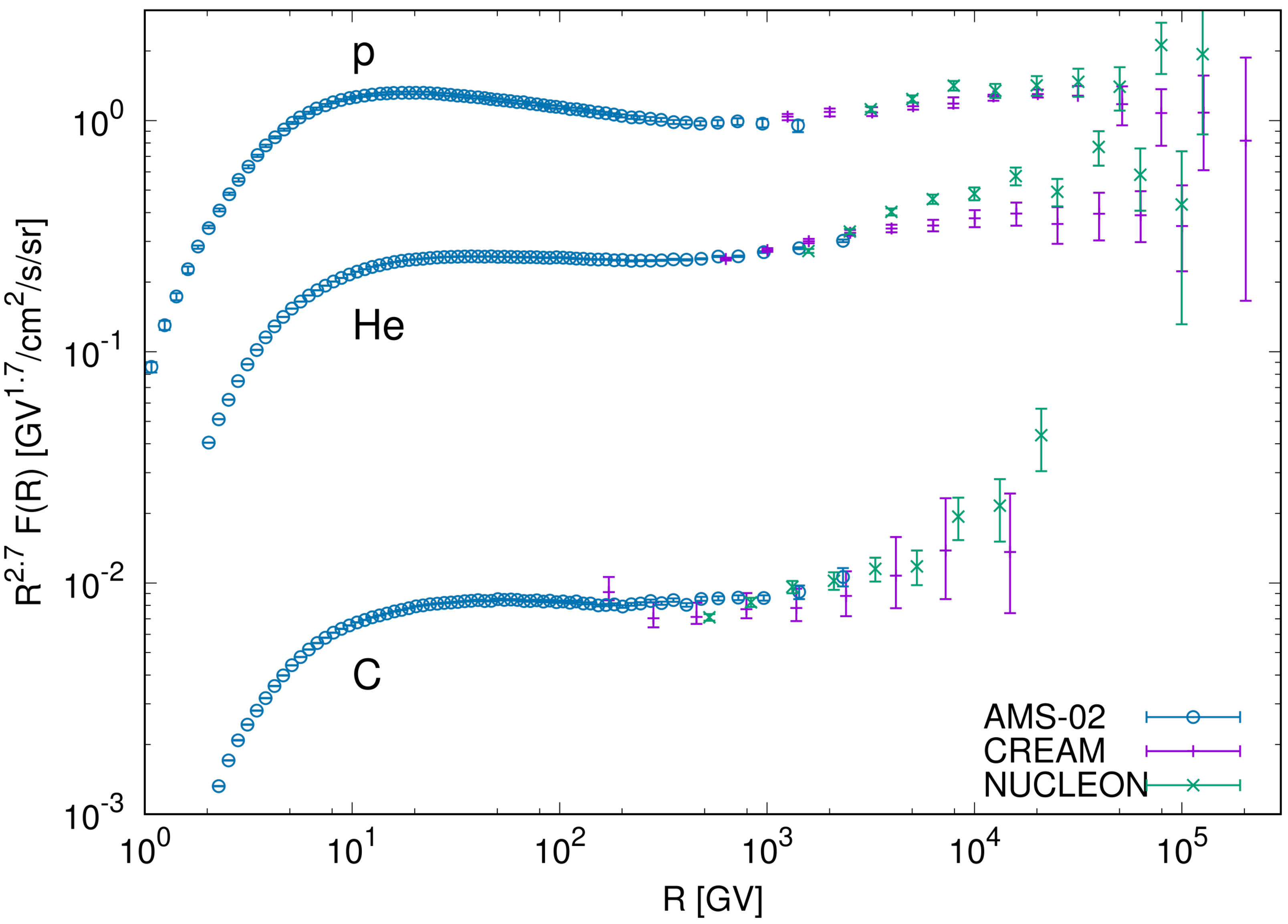




AMS-02 and CALET agree very well

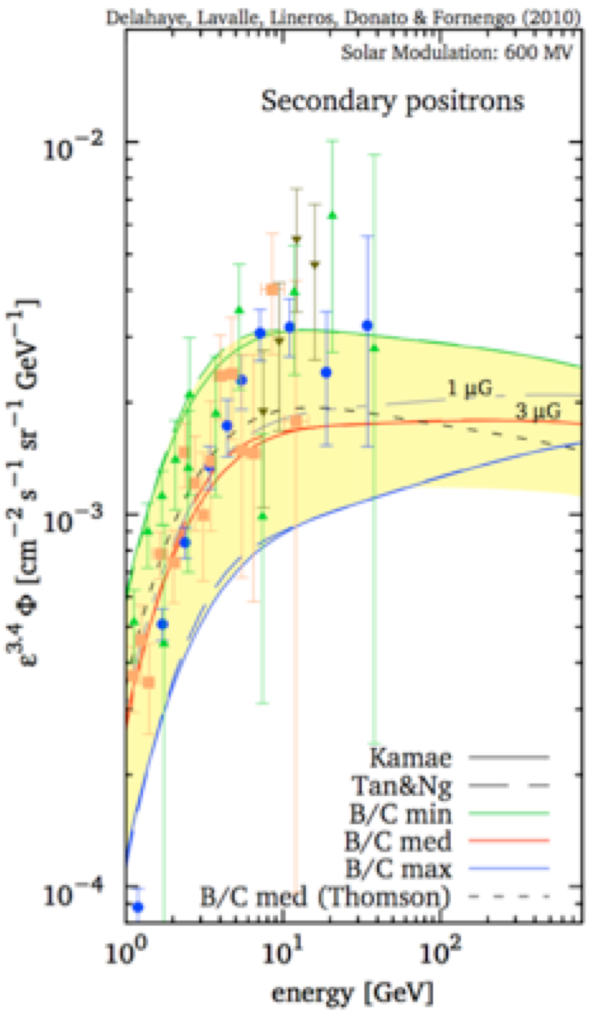


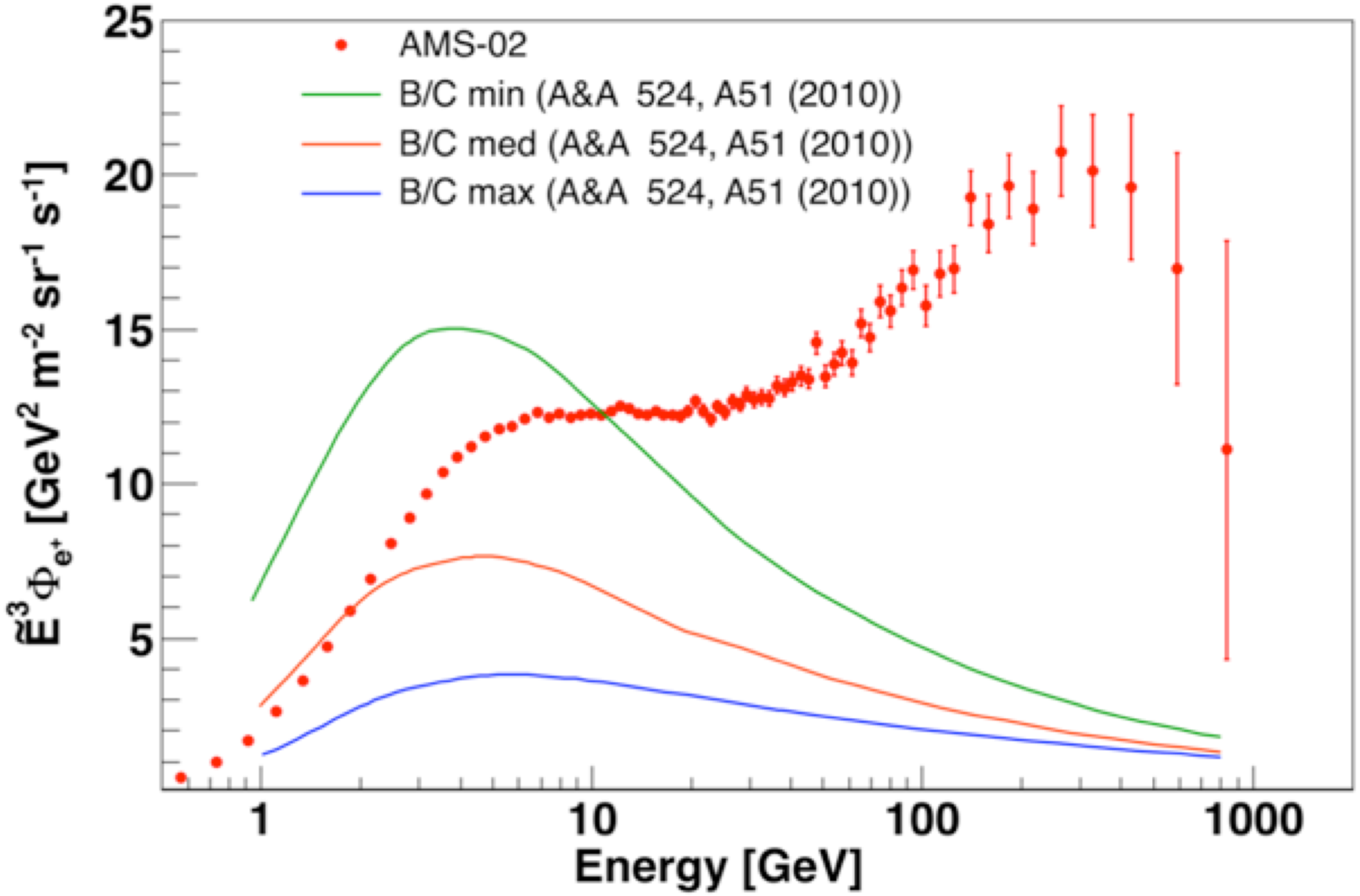
Mild tensions with DAMPE!



p
He
C
$R^{2.7}$ F(R) [$GV^{1.7}/cm^2/s/sr$]
R [GV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^0
10^1
10^2
10^3
10^4
10^5
AMS-02
CREAM
NUCLEON

With some interesting 'anomalies'





Most **common** explanation : Annihilating Dark Matter (dozens of papers fitting WIMP models)

Most **likely** explanation :

Secondary production in spallation at a nearby old SNR (**Mertsch et al** . *Phys.Rev.D* 104 (2021) 10, 103029)

The existing detectors

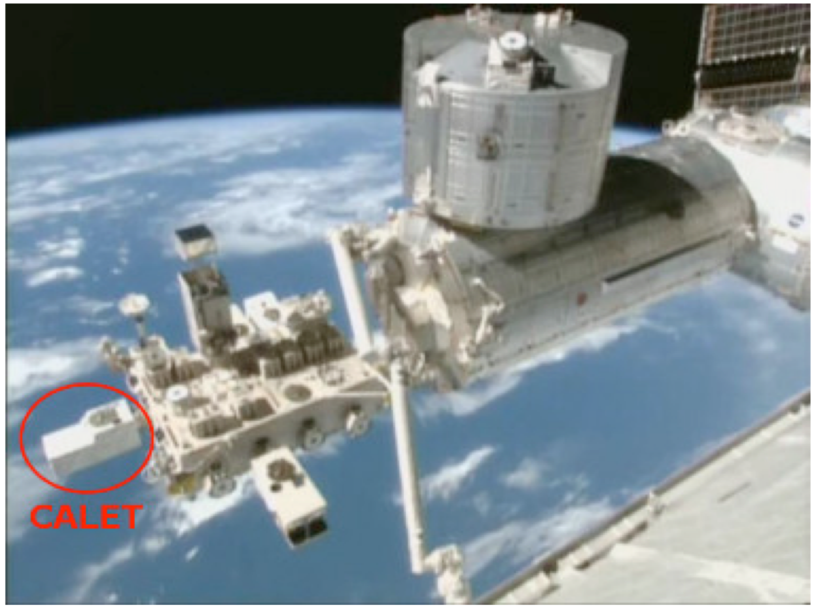
7 ton payload onboard the ISS
Permanent magnet and 8 detectors. TOF detector from scintillation counters, Silicon strip detectors, Ring Imaging Cherenkov Detector, Electromagentic Calorimeter (alternating layers of scintillator fibers and lead foil)
Caliberated in an accelerator beam at CERN

Few antihelium/antihelium-3 events claimed.

Calorimetric detector, no magnet (calibrated in Orbit using the Earth's magnetic field). Order of magnitude higher detection range than AMS-02

DAMPE :
China+Italy+Switzerland

The existing detectors (contd)

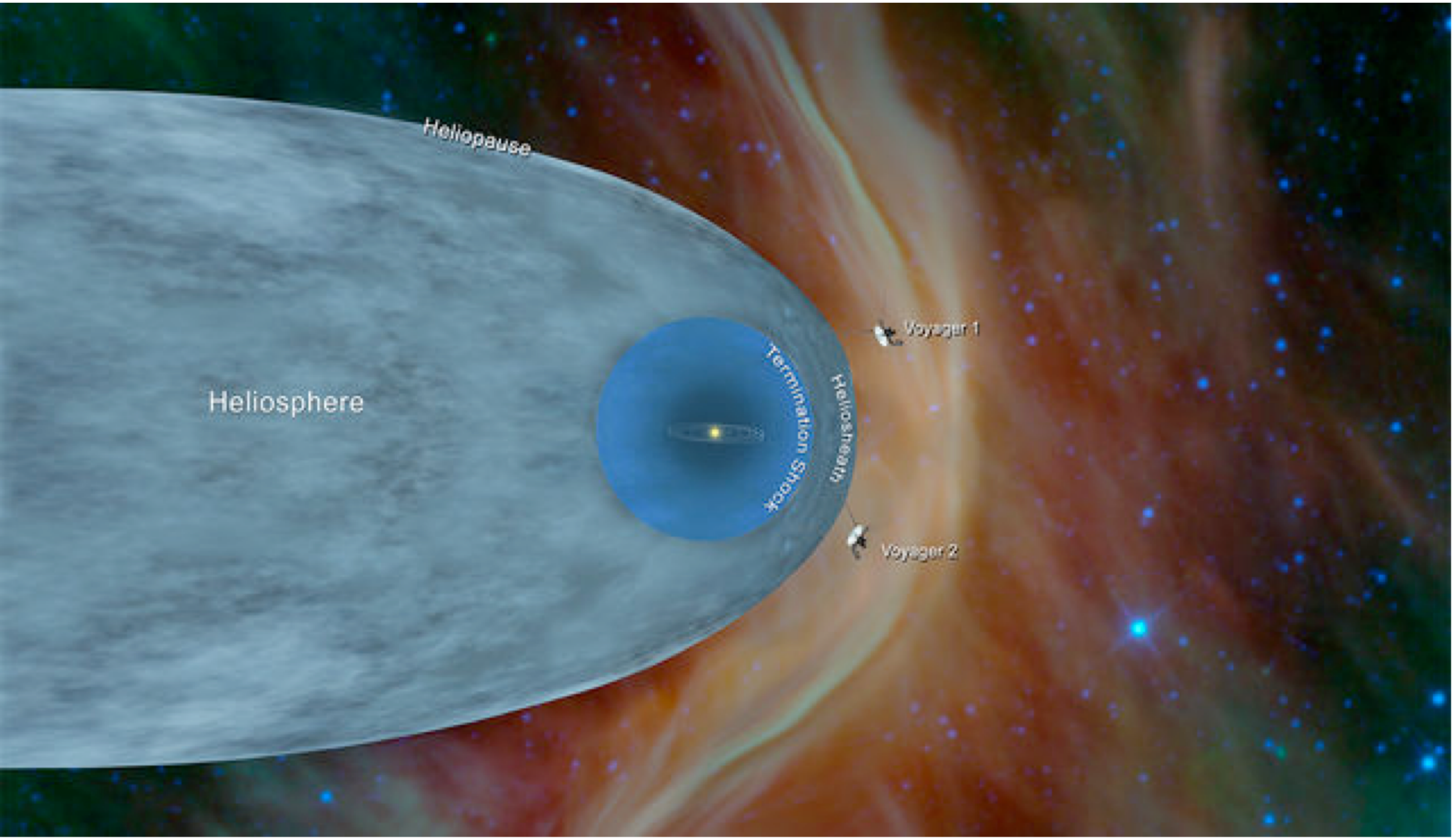


Also on the ISS, 650 kg (JEM Kibo)
Calorimetric, charge identifying detector made of plastic scintillators
3 radiation length thick imaging calorimeter with Tungsten and scintillating fiber layers. Lead Tungstanate Hodoscope. Optimized to measure electron spectrum.

All recent measurements have been made at orbits very close to Earth

Instrument	Weight (kg)	Orbit	Mission duration (years)
AMS-02 (ISS)	6717	Lower Earth	10+
DAMPE	1400	Sun Synchronous	3 (P), 6+
CALET (ISS -JEM Kibo)	650	Lower Earth	6+

Except for the Voyager Satellites (156 AU away), also Pioneer 10



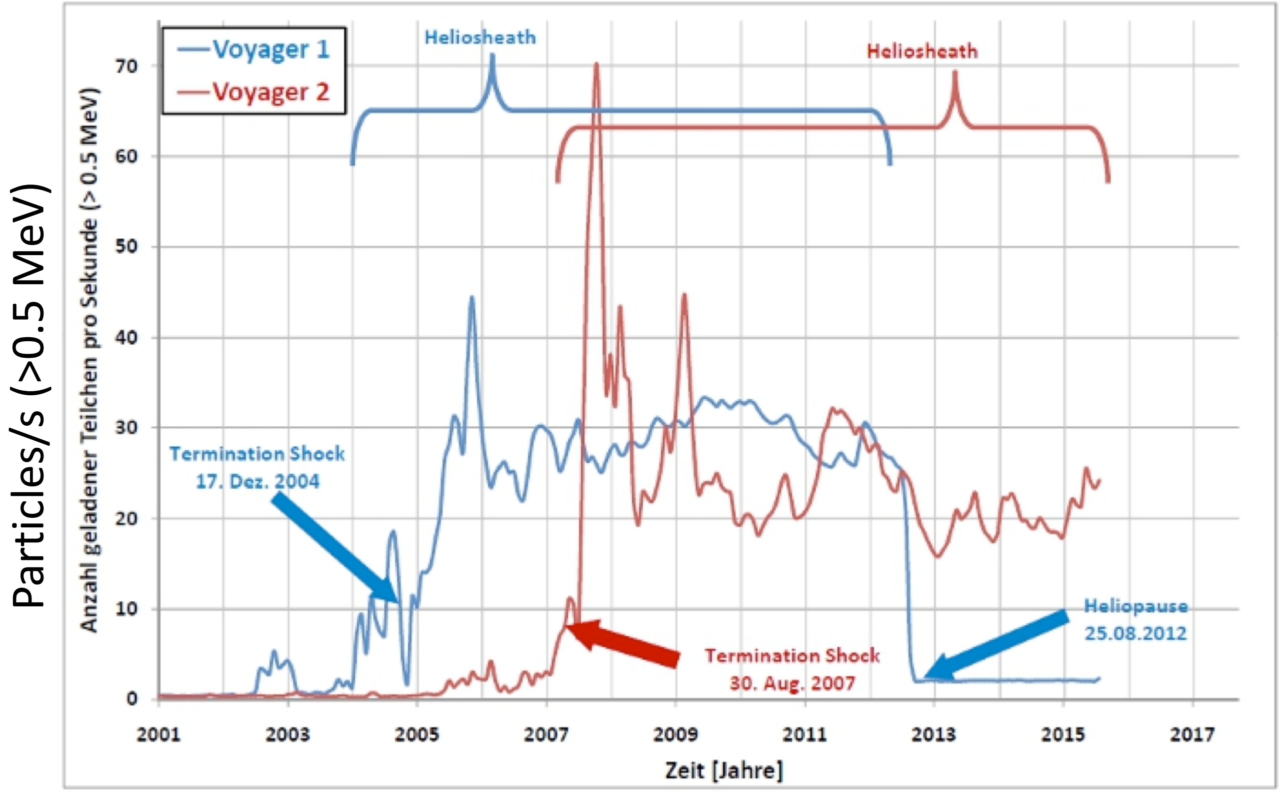
The heliosphere is expected to have no impact on CR flux/spectra/composition above 50 GV

The heliosphere itself is inside a local bubble, 300 light years across (known only from UV astronomy). (1/10th the average density of ISM in the milky way)

The local bubble is not accounted for in any CR propagation modelling. Heliosphere is accounted only as its magnetic field

Voyager	773 (kg)	Deep Space	45+

Voyager 1



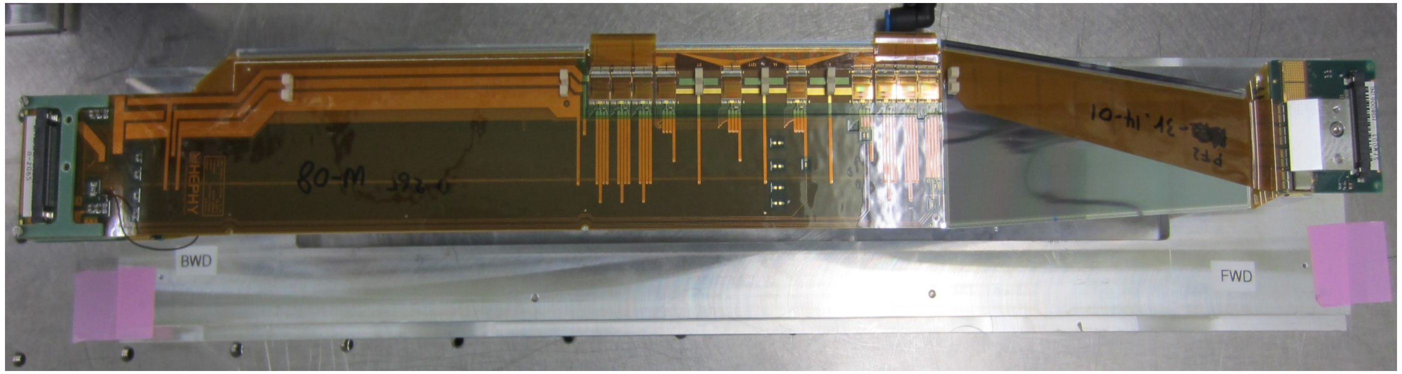
Had a magnetometer, a Plasma spectrometer (5 eV to 1 keV), Cosmic Ray system, Plasma Wave experiment.

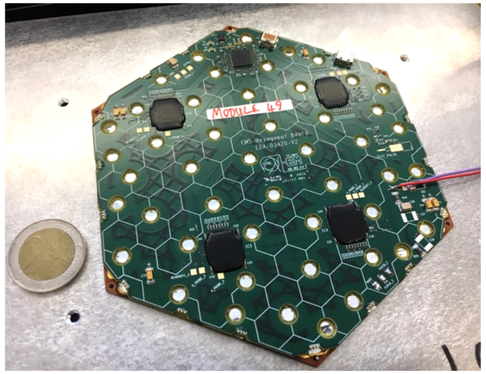
Data from Voyager 1 has changed many of our views about the heliosphere

Bow shock - > Bow wave

Solar Magnetic field appears to be aligned to the Galactic Magnetic Field.

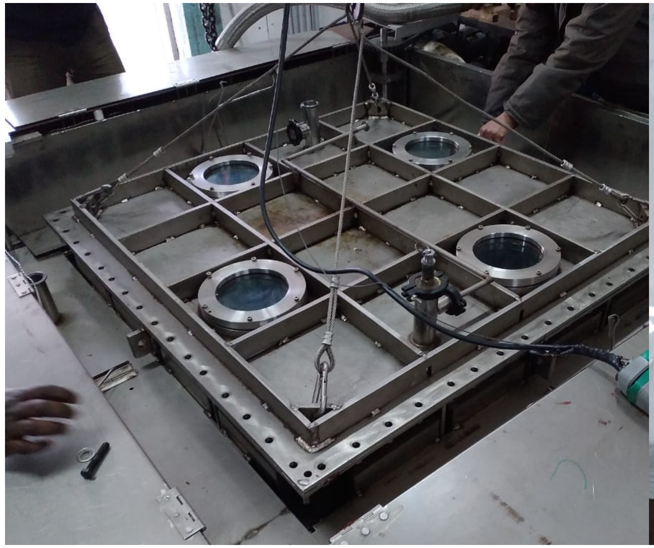
We can make





Silicon Detectors

Plastic Scintillators



As well as inorganic scintillating crystals (at BARC), and cutting edge DAQ electronics

ISRO has launch capabilities

SLV-3

Height	: 22.7m
Lift-off weight	: 17 t
Propulsion	: All Solid
Payload mass	: 40 kg
Orbit	: Low Earth Orbit

ASLV

Height	: 23.5m
Lift-off weight	: 39 t
Propulsion	: All Solid
Payload mass	: 150 kg
Orbit	: Low Earth Orbit

PSLV-XL

Height	: 44m
Lift-off weight	: 320 t
Propulsion	: Solid & Liquid
Payload mass	: 1860 kg
Orbit	: 475 km Sun Synchronous Polar Orbit (1300 kg in Geosynchronous Transfer Orbit)

GSLV Mk II

Height	: 49m
Lift-off weight	: 414 t
Propulsion	: Solid, Liquid & Cryogenic
Payload mass	: 2200 kg
Orbit	: Geosynchronous Transfer Orbit

GSLV Mk III

Height	: 43.43 m
Lift-off weight	: 640 t
Propulsion	: Solid, Liquid & Cryogenic
Payload mass	: 4000 kg
Orbit	: Geosynchronous Transfer Orbit

One or more high endurance deep space mission(s)

•Quantify and scrutinize the peculiarities of our local environment in the current understanding of astroparticle physics, by measuring large-scale spatial and temporal variations of the flux and spectra of cosmic rays within and in the neighborhood of the heliosphere over a multi decadal timescale.

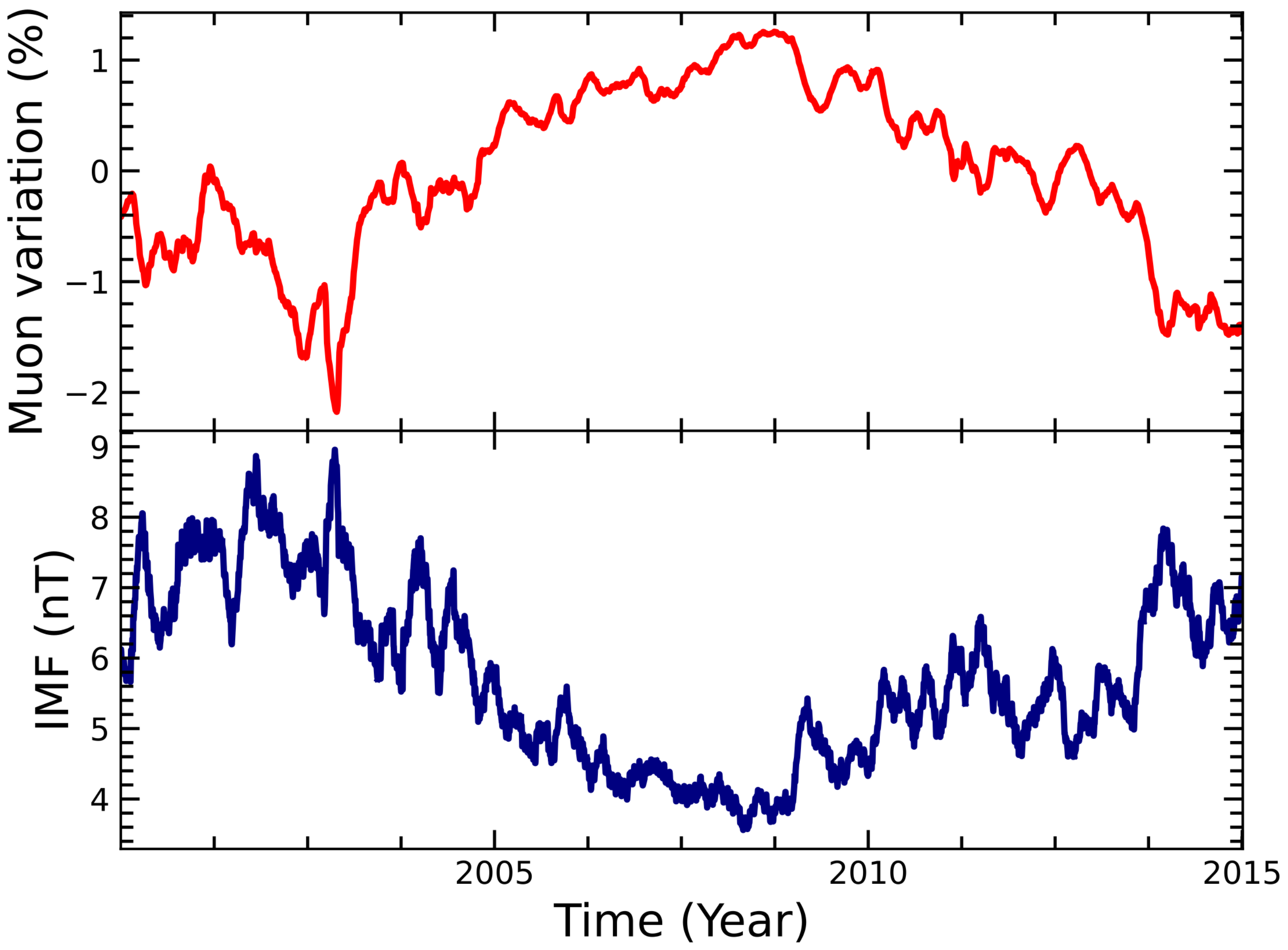
•Tackle open problems in astroparticle physics such as the mechanism of acceleration of cosmic rays and the nature of dark matter.

•Build a detector more like DAMPE than AMS (in cost) but optimized towards lower energies and for very long mission lifetime, and send it on Voyager like trajectories.

•Better understanding of reacceleration within and near the heliosphere.

Build a 4 dimensional map of the heliosphere over 2 to 4 decades from launch.

Space weather and Earth climate modelling



The muon flux as observed at GRAPES-3 shows excellent correlations with both upper atmospheric temperature and the IMF.

Using the former as a probe of either of the latter ultimately involves a hierarchical model of magnetic fields, CRs and plasma within the heliosphere as a whole

I guess we can all appreciate how developing new data inputs for climate modelling is important over the coming decades

Conclusions

The current status of cosmic ray physics is overwhelmingly reliant on data gathered from orbits close to Earth, and makes unphysical, simplifying assumptions about the local environment.

Measurements of the spatial and temporal variations over multiple decades, at intermediate energies (~GeV) CR flux, spectrum and composition in our heliosphere and beyond can cause a paradigm shift in cosmic ray physics.

The idea is merely being conceptualized, and is an attempt to channel locally available resources towards a future experiment.